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Abstract

Aluminum alloys are the prime metallic materials used for light weight industrial applications. Experimental characterization of the damage in AA 2024 T3 alloy subjected to close-in blast loading is one of the critical steps to assess and improve the safety of the passenger and cargo transportation systems. Currently, several aluminum alloys are also considered by the DoD for applications such as armor for vehicles and other protection systems. AA 2024 T3 series alloys have complex microstructure, fatigue resistance, and exhibit good strength to weight ratio. They are resistant to uniform corrosion but highly susceptible to localized corrosion. An initial study of the failure mechanism of AA 2024 T3 alloy subjected to close-in explosive loading is currently underway at the U.S. Army Research Laboratory. The effect of the explosion on the microstructure and the microhardness of this alloy as a function of the distance from the center of explosion are studied by scanning electron microscopy, x-ray diffraction, energy dispersive spectroscopy, and Knoop microhardness. In addition, the position of the initiation of the alloy failure, as shown in obtained videos, is also studied in conjunction with the propagation of the damage wave through the alloy.

Introduction

The objective of the analysis is to study possible microstructural and stoichiometric variation of the AA 2024 T3 alloy as a function of the distance from the center of the explosion to the perimeter of the panel. The topographical observation of the surface of the aluminum

alloy was conducted for detection of immediately recognizable microstructural and chemical differences. Detailed characterization was conducted with the use of scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD) and Knoop hardness testing. In an effort to minimize the statistical variation, the data were collected from many different areas of the specimens. However, special attention was given on certain points of the specimen where there was a deviation from the average characteristics of that particular area.

Experimental

Two panels were characterized for this study after the close-in blast tests. Both panels were subjected to one unit charge of C4 explosive. The panels were 0.18 cm thick, 121.9cm square, and clamped over a 7.62 cm wide area at the boundary. The closest approach distance from the nearest edge of the charge to the center of the panel surface was 4.83 cm for the first panel and 7.12 cm for the second panel. The first panel failed (blast penetrated through) but the second panel did not. The first panel will be referred to as the “ruptured” panel and the second panel as the “not-ruptured” panel.

From the ruptured panel, five sample pieces were obtained. The pieces were labeled I, II, III, IV and V respectively. Sample I is at the center of the explosion, while sample V was chosen at an area of the panel not affected by the explosion. The samples from this ruptured panel before getting cut into individual pieces for the analyses, are shown in Figure 1. For the not-ruptured panel, a triangular sample was removed from the center of the panel, similar in location to samples I through III of the ruptured panel (see Fig. 2). SEM and EDS analyses were conducted by using the FEI Nova NanoSEM600 microscope and EDAX Genesis, respectively. XRD analysis was conducted by using a Rigaku MiniFlex II Desktop X-ray Diffractometer. The x-ray was a CuK α 1 radiation of wavelength $\lambda=0.15406$ nm, at 2.0 degrees/min scan speed and 0.02 degrees sampling width. The hardness of the alloy was measured by using a Wilson Rockwell, Wilson Instruments, hardness tester.

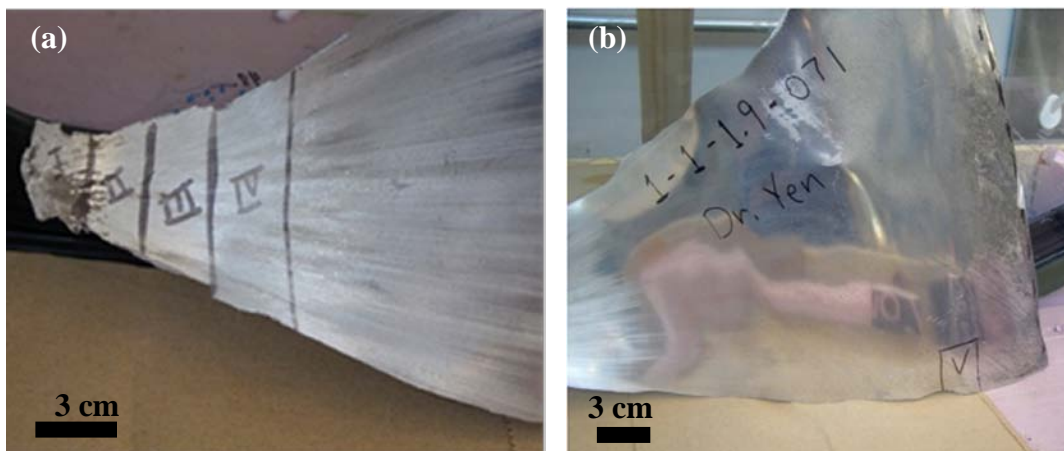


Figure 1. Sample areas (a) I through IV, and in (b), V from the ruptured panel.



Figure 2. Triangular sample examined from the not- ruptured panel, in relation to the blast area

Results

SEM and EDS Analysis

Evaluation of the sample surfaces by the SEM of samples I through IV of the ruptured panel indicated a gradual change in surface deformation. Figure 3 (a) shows the heavily damaged region in sample I of the ruptured panel. The damage in sample I shows examples of ductile failure by void coalescence. The damage in sample II through IV shows voids, but none of the higher energy failures that were observed closer to the blast. Fracture by cracking has been observed in sample I through sample IV areas, but not in sample V.

For the not-ruptured panel, similar gradual change in surface deformation was observed away from the explosion. However void coalescence was not observed on surfaces close to the blast center (see Fig. 3 (b)). As with the ruptured panel, cracks were observed throughout the sample.

EDS analysis of surfaces from all samples from the ruptured panel and not-ruptured panel were conducted. No significant difference was observed between the two panels. The observed sample chemistries, though not always consistently, were Al, Cu, Mg, Zn, Mn, Si, Fe, Ti, and Cr, as shown in Figure 4. This is in agreement with the typical AA 2024 composition [1]. But the current analysis also showed traces of S, Na, K, N, O, Ag, and C on the surface. It is very possible that these are residual elements that became situated on the sample surfaces from the blast.

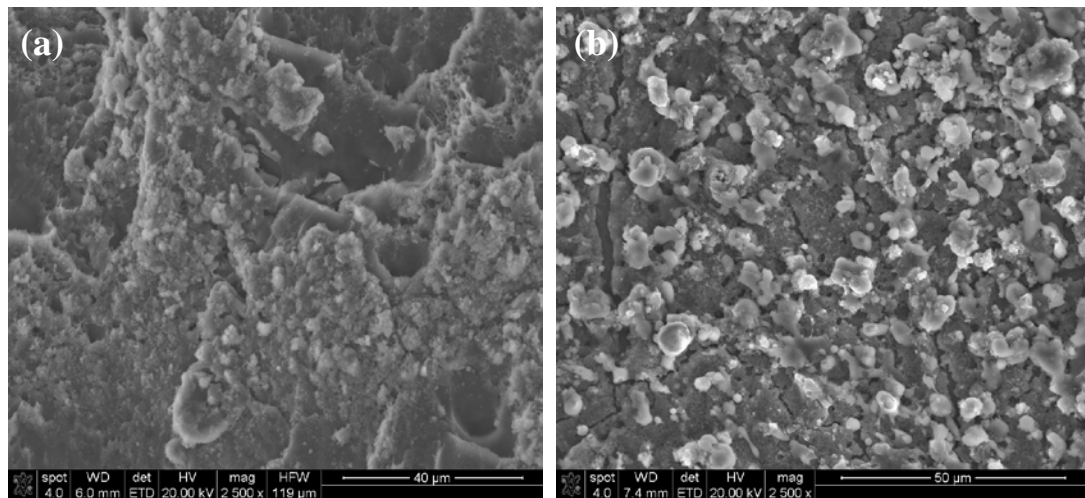


Figure 3. Damaged surfaces from (a) sample I by the blast center from the ruptured panel, (b) area by the blast center from the not-ruptured panel. Both images were captured at the same SEM conditions and magnifications.

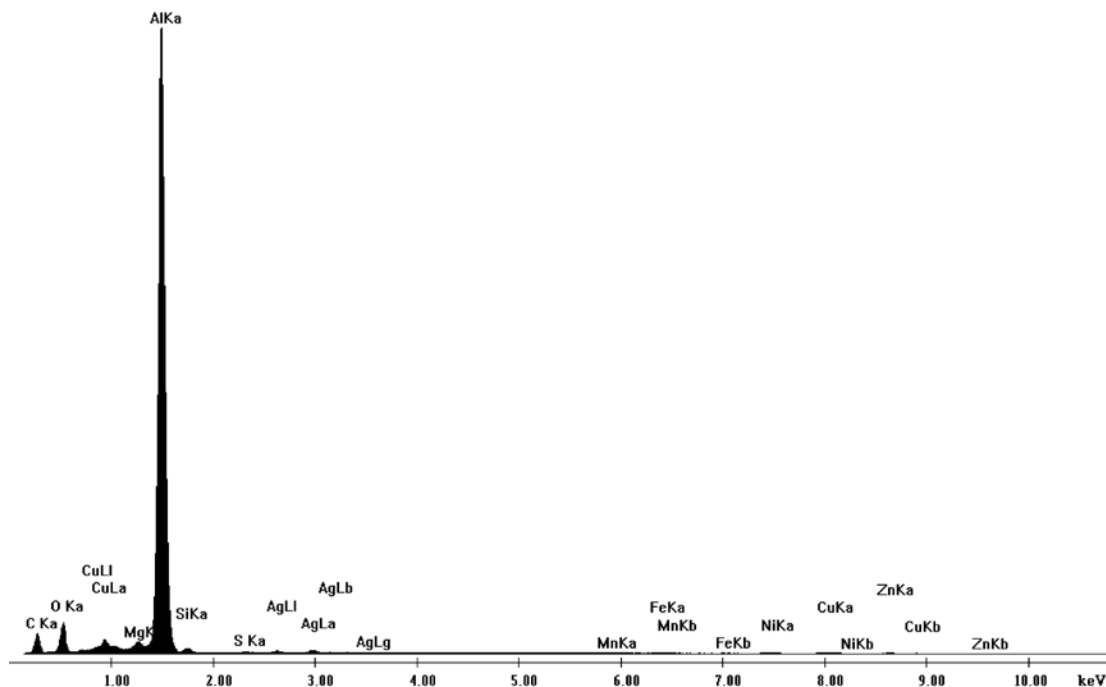


Figure 4. An example EDS spectra

X-ray Diffraction Analysis

The effect of the blast on the microstructure of ruptured AA 2024 T3 panels was studied by x-ray diffraction (XRD) as a function of the distance away from the center of the explosion according to Figure 1. A summary of the XRD results is shown in Figure 5. Since sample Area V of the panel at roughly 40 cm from the center of the explosion was not deformed (Fig. 1) by

the explosion, we consider its XRD spectrum as the reference for the analysis. The XRD spectra displayed the typical spectrum of aluminum and showed that the explosion did not create any new phases. The first five diffraction peaks of the reference XRD spectrum appear on all the

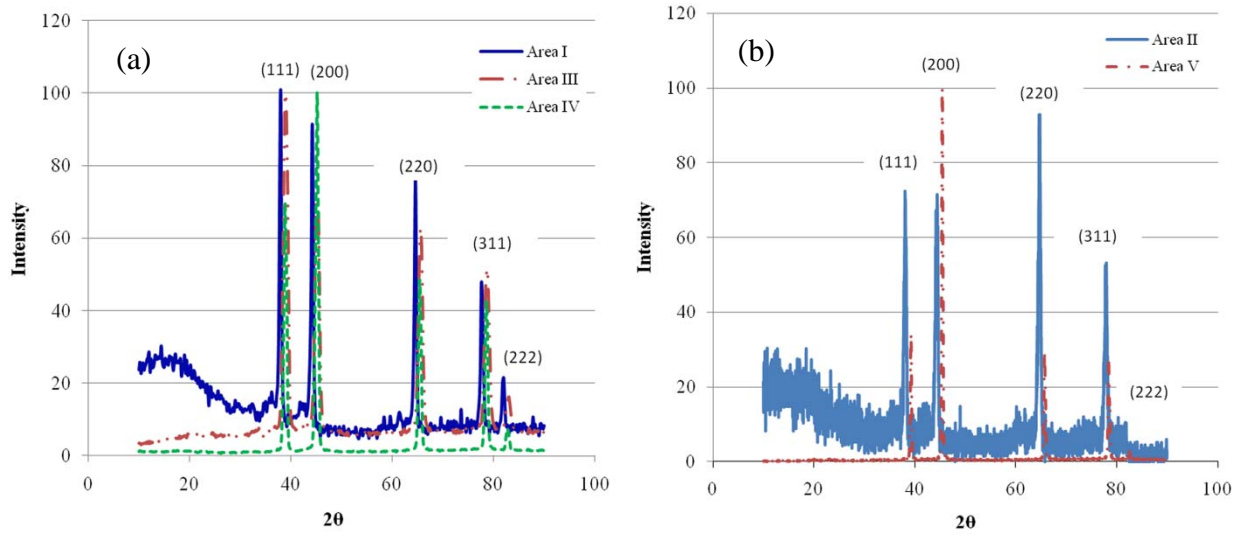


Figure 5. (a) XRD spectrum from Area I, Area III and Area IV and (b) XRD spectrum from Area II and Area V from the ruptured panel

Table T1. Interplanar spacing variation across the ruptured panel

Interplanar spacing (Å)	Sample Area				
	Area I	Area II	Area III	Area IV	Area V
d ₁₁₁	2.37	2.36	2.26	2.32	2.29
d ₂₀₀	2.05	2.04	1.97	2.01	1.99
d ₂₂₀	1.44	1.44	1.41	1.43	1.42
d ₃₁₁	1.23	1.23	1.20	1.22	1.22
d ₂₂₂	1.17	1.18	1.16	1.16	1.17

Table T2. Lattice parameter variation across the ruptured panel

Lattice Parameter (Å)	Sample Area				
	Area I	Area II	Area III	Area IV	Area V
a ₁₁₁	4.10	4.08	3.91	4.01	3.97
a ₂₀₀	4.09	4.07	3.93	4.01	3.99
a ₂₂₀	4.08	4.07	3.987	4.03	4.02
a ₃₁₁	4.07	4.07	3.99	4.03	4.04
a ₂₂₂	4.08	4.07	4.00	4.04	4.04
a ₀ (aver)	4.08	4.07	3.96	4.02	4.01

other XRD spectra (Figure 5 (a) and (b)). However, depending on the distance of the sample from the center of explosion, a shift of all the XRD peaks with respect to the reference XRD peak is observed, an indication of local deformation. Table T1 and T2 show the variation of the interplanar spacing and lattice parameter across the panel as a function of the diffraction peak and distance away from the center of explosion. The strain across the panel was computed as follows:

$$\bar{\varepsilon} = \frac{\sum \varepsilon_{hkl}}{5} \quad (1)$$

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{ref_hkl}}{d_{ref_hkl}} \times 100 \quad (2)$$

where: $\bar{\varepsilon}$ is the average strain

ε_{hkl} is the stain in the (hkl) interplanar spacing

d_{ref_hkl} is the (hkl) interplanar spacing of the reference spectrum and

d_{hkl} is the is the (hkl) interplanar spacing

Figure 6 shows that at the distance of 7.6 cm from the center of the explosion (at Area III) the strain changed from tensile to compressive and it changed to tensile strain again at distances larger than 7.6 cm. Relative videos of the panel response to the explosion showed that the rupture of the panel initiated at about 7 cm from the center of the blast, in agreement with the measured strain.

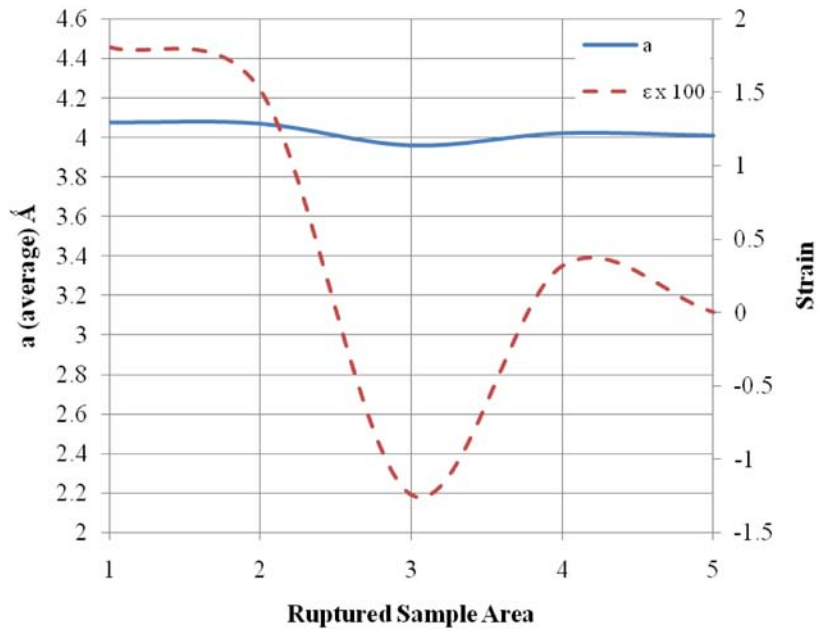


Figure 6. Lattice parameter, a , and strain variation from the explosion center

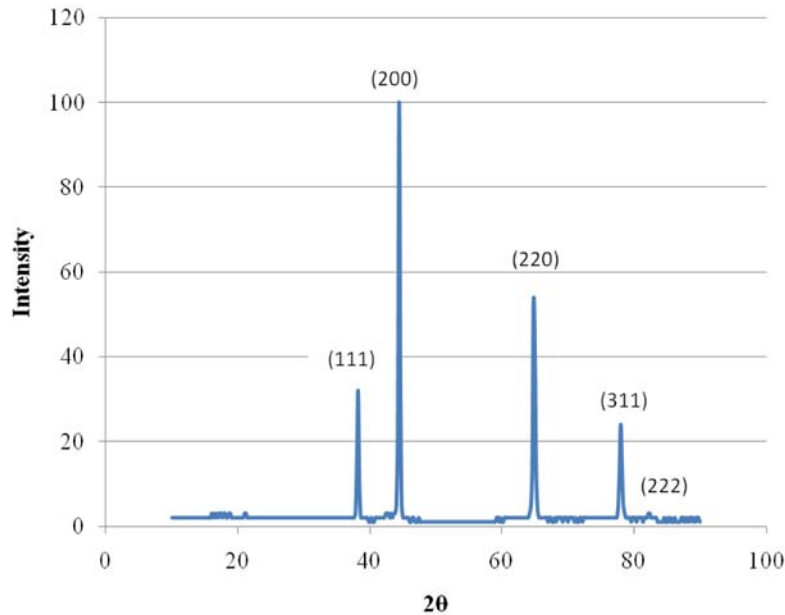


Figure 7. XRD spectrum around the impact area of not-ruptured Al 2024 T3 panel

Figure 7 shows the XRD spectrum of the not-ruptured Al 2024 T3 panel. The XRD spectrum was similar to the XRD spectrum on the ruptured panel. There was also no indication of new phase formation due to the explosion. The average lattice parameter was 4.04 \AA . The strain around the impact area was 0.79%, which was computed using Equation 1 with respect to the reference XRD interplanar spacing. The strain of the second, not-ruptured panel was 130% smaller than the corresponding strain of 1.81% at Area I of the first ruptured panel. This indicates that smaller stresses were experienced in the not-ruptured panel.

Ultimate Tensile Strength (UTS) Measurement

The UTS of both ruptured and not-ruptured AA 2024 T3 panels was determined by converting the measured Rockwell Hardness B values across the panels into strength. A summary of the average UTS across the ruptured panel is shown on Figure 8. The average UTS of the non deformed part of both panels varied from 415 (not deformed) to 440 (deformed) MPa. These values agree well with the published values of the AA 2024 T3 alloy [2]. The average 6% UTS increase of the deformed part of both panels, compared to the non affected part of it, is attributed to the strain hardening of the alloy due to the explosion.

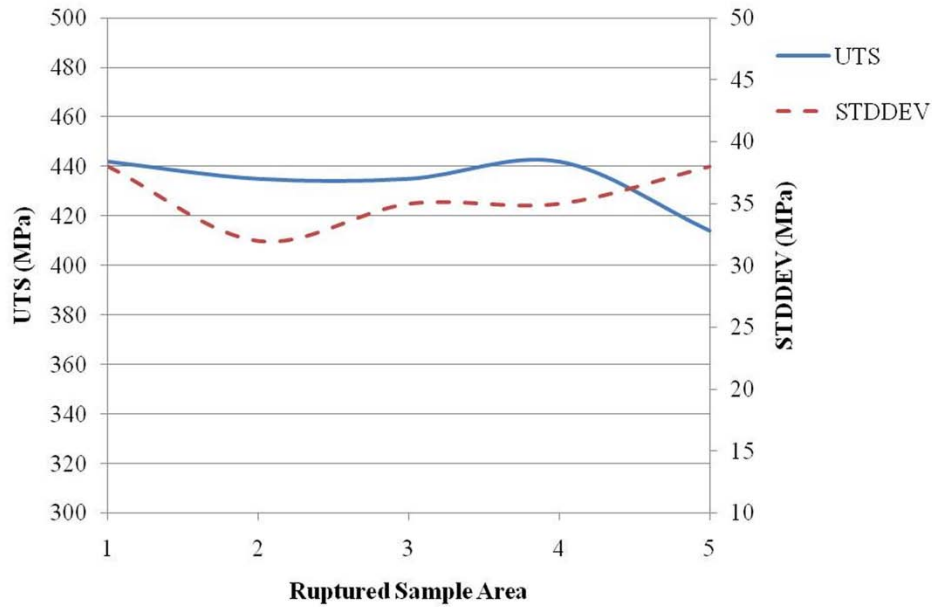


Figure 8. Average UTS across the ruptured Al 2024 T3 panel

Conclusions

Two AA 2024 panels subjected to close-in blast loading, one ruptured and the other not-ruptured, were characterized for possible microstructural and strain variation as a function of the distance from the center of the explosion. Neither significant microstructural nor chemical differences were detected. However XRD results showed a tensile to compressive to tensile strain variation outwards from the center of the blast. The difference in the performance of the plates appear to be due to experimental variation causing strain hardening from the blast.

References

- [1] The Aluminum Association, *International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys*, www.aluminum.org, 2009.
- [2] W. D. Cullity, *Materials science and engineering. An introduction*, Wiley, 5th Edition, 2000, p 798

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